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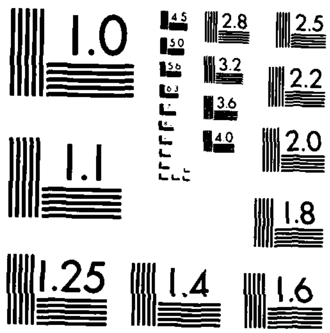

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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.202

TECHNICAL EVALUATION REPORT

on

AVIONICS PANEL SPECIALISTS' MEETING

on

DIGITAL OPTICAL CIRCUIT TECHNOLOGY

by

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University of Arizona
Tucson, AZ 85721
USA

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TECHNICAL EVALUATION REPORT

Professor Hyatt M. Gibbs, Ph.D.
Optical Circuitry Cooperative and Optical Sciences Center
University of Arizona, Tucson, Arizona 85721 USA

PURPOSE AND THEME

The purpose of the meeting was to present the research and development status of optical circuit technology and to examine its relevance in the broad context of digital processing, communication, radar, avionics, and flight control systems implementation.

The following statement of the theme and objectives from the meeting announcement outlines the rationale for a reexamination of digital optical circuitry with an emphasis on all-optical systems employing nonlinear materials:

> "In the future it will be important that systems be designed which fully utilize the capabilities of optical devices. Such systems which exploit the potential speed and bandwidth capability of optical devices, and their capability for parallel processing of information should find significant applications in the communication, computing and radar fields. Technology advances of the past decade in optical electronics and very recent laboratory achievements may make possible all-optical, high-speed, EMI/EMP immune digital computers and data distribution systems. As a result of these advances in technology, there are now available sources, detectors, optical waveguides, bi-stable optical devices, modulators and demodulators capable of providing bandwidths well in excess of one gigabit. This availability is stimulating the examination of novel applications and a refinement of device performance goals is now required.
>
> The motivation for all-optical digital systems is derived from the need to satisfy requirements for:
>
> --Very high integrity systems
> --Wide-bandwidth data distribution
> --High speed
> --Real-time bulk processing
> --Low cost
> --Elimination of optical to electronic interfaces
>
> The optical processing field is replete with technical approaches and to some extent there is an inadequate understanding of the organization of the problem area. The proposed meeting on digital optical circuits will aid those on the periphery of this technology to understand its goals, approaches, and state of the art. The researchers and engineers who work in this particular area will have the opportunity to meet with their colleagues and discuss the technical details of this highly specialized field. The state-of-the-art realizations and potential of optical circuit technology are also of interest to a broad applications-oriented audience concerned with digital data processing, communications, radar and avionics.
>
> Heretofore, conferences dedicated to the subject of linear or two dimensional optical processing have over-shadowed the subject of non-linear, guided wave, optical bi-stability circuits. Recent advances with non-linear and bi-stability effects have focussed attention on the possibilities for optical digital circuits. These circuits will result from a blending of non-linear materials, integrated optics technology and picosecond techniques. It is this latter subject area that the proposed technical Specialists Meeting on Digital Optical Circuit Technology will focus upon. The Electromagnetic Wave Propagation Panel is assisting in the preparation of this Meeting."

EVALUATION

a. Materials

Nonlinear optical signal processing can best be done with very large nonlinearities that operate at room temperature, require very low power per logic element (microwatts), and are very fast (picosecond). No such material has been discovered or constructed so far. For most applications other than a large stationary computer, room-temperature operation is highly desirable if not absolutely essential. GaAs, in both bulk and multiple-quantum-well (MQW) structures, is the most promising candidate at present (talk 8; see Appendix A for talk titles and authors). It is also attractive in other ways: well-developed and commercially available diode lasers have enough power and the appropriate emission wavelength to drive GaAs nonlinear optical devices; GaAs can be used to fabricate lasers, detectors, and high-speed electronics, making it a natural material for integrated optical circuitry; a substantial base of knowledge and of growth and fabrication equipment already exists for GaAs.

Other semiconductor materials with large (≈ 1 to 10^{5} cm^2/kW) optical nonlinearities are being investigated: InSb (5 µm, one-photon band filling, 77 K; talk 1); InSb (10 µm, two-photon band filling, 300 K; talk 1); CdS (0.49 µm, bound exciton, 4 K, talk 2); CuCl (0.39 µm, biexciton, 5 K; talk 6 and Ref. 1); InAs (3 µm, one photon band filling, 77 K; Ref. 2) $Cd_xHg_{1-x}Te$ (10 µm, one-photon band filling, 77 K; talk 3); $Cd_xHg_{1-x}Te$ (10 µm, two-photon, 300 K; talk 3); ZnS (0.46 to 0.64 µm, thermal, 300 K; talk 8);

ZnSe (0.51 to 0.65 μm, thermal, 300 K; talks 8 and 9). Semiconductor resonantly enhanced interactions have short absorption depths ($\approx$ 1 μm), permitting very short and fast decision making devices.

Pipeline data applications may use guided-wave devices with lengths from one to several millimeters; semiconductors can be used farther off resonance or in overlays in which only the evanescent field experiences the nonlinearity. The much longer interaction distances make the much smaller (10^{-9} to 10^{-8} cm^2/kW, i.e., very large compared with other known nonresonant nonlinearities) but faster nonlinearities of some organic materials attractive (Ref. 3).

Clearly the search for larger and faster nonlinearities, especially those still effective at room temperature, should continue.

b. Devices

Nonlinear optical devices for signal processing can be classified roughly into two categories: nonlinear etalons in which the light beams travel perpendicular to the plane of the etalon and nonlinear waveguide devices in which the light is guided through the nonlinear medium.

1. Etalons

Nonlinear etalons are attractive for parallel processing because up to a million beams could be focused on a single etalon, defining an independently functioning pixel for each beam. In the space between the nonlinear etalons the beams can be directed, imaged, or transformed by linear optical devices; the beams can pass through each other without interfering. That is, the power and advantages of optics can be fully utilized, and the nonlinear etalons make the logic decisions.

A thin film of nonlinear medium can exhibit optical bistability or thresholding, for example, by three different mechanisms: absorptive and/or dispersive bistability with external feedback or by increasing absorption bistability with only intrinsic feedback. The lowest powers, fastest speeds, and highest transmissions have been achieved using dispersive bistability. The most promising devices to date are GaAs (talk 8) etalons and ZnS (talk 8) and ZnSe (talks 1, 8, and 9) interference filters for room-temperature parallel processing.

If one imposes a maximum heat load of 100 W/cm^2, consistent with some electronic designs, one can extrapolate present-day one- or few-beam experiments as follows. An array of 10^6 spots with 10 mW per spot could run cw or up to 10 KHz on a 5-cm^2 ZnS interference filter assuming 25% absorption (i.e., up to 10^{10} operations per second). An array of 10^6 NOR gates with 1 pJ per gate could run at 100 MHz on a 1-cm^2 GaAs etalon (i.e., up to 10^{14} operations per second). Clearly lower powers are desirable, but these numbers are becoming reasonable enough to warrant the design of special-purpose few-pixel demonstrations in order to study other problems associated with parallel processing of multiple beams: crosstalk via diffraction, diffusion, or luminescence; heat dissipation; and uniformity of thickness; for example.

Nonlinear etalons are able to perform all of the basic logic operations (talks 1, 2, 3, 8, 9). Under certain conditions the transmission of a nonlinear etalon can become unstable; that is, for a noise-free steady input intensity, the output intensity can become time dependent. If the round-trip time t_R exceeds the medium response time τ_M, the output may undergo very regular oscillations with a period of $2t_R$. As the values of τ_M are reduced, faster and faster all-optical oscillators can be constructed (talk 4).

Most of the device research is directed toward the improvement of the most promising nonlinear etalons. But it is important to pursue studies of fundamental limits, such as determining the smallest number of nonlinear atoms required for bistability and achieving bistability without a cavity (talk 7).

2. Waveguides

Waveguides permit the maintenance of high light intensity over long propagation distances. Only the largest nonlinearities are useful for nonlinear etalons because diffraction limits the strong-focus length (the Rayleigh length = $\pi w_0^2/\lambda$, where w_0 is the beam waist at the focus and λ is the wavelength) to micrometer distances. In contrast, smaller and perhaps faster nonlinearities can be useful for guided-wave devices. Of course, the transit time increases with interaction length. But in pipelining applications, such as data encryption and decoding, transit time is unimportant provided the medium response is fast enabling a short time between pulses.

The development of all-optical waveguide bistable devices has lagged behind that for etalon devices. There have been a number of hybrid devices utilizing waveguide modulators. With fast detectors and amplifiers, hybrid devices can operate in tens of nanoseconds with very low optical powers. External amplifiers and power supplies can be eliminated if millisecond response time is acceptable. Fast hybrid devices might be the best way to harden sensitive detectors and/or eyes against lasers. High-speed optoelectronic switches may be useful in this context (talk 13). Particularly attractive are devices based on interferometric modulators such as the Mach-Zehnder directional coupler modulator (talk 10).

All-optical waveguide devices are in an early stage of development with the emphasis upon feasibility studies. The guide material can be nonlinear in principle, but the common materials for constructing waveguides are not always the most nonlinear. And the nonlinear materials often have losses preventing propagation distances of several millimeters. The solution being tried in several labs is to overlay the nonlinear material on top of a conventional waveguide. The evanescent wave can be adjusted to give the desired phase shift with acceptable losses in distances convenient for waveguide construction. Talk 5 discusses liquid CS_2 contacted to a waveguide prepared by silver-sodium ion-exchange in Schott glass type F5. Light of 1.06-μm from a Nd:YAG pulsed laser is prism-coupled or endfired into the nonlinear waveguide structure. The response time of the CS_2 should be 1 to 3 ps, but

the response has not been studied with subnanosecond resolution. Polydiacethylene has a higher $\chi^{(3)}$ and should also be subpicosecond. Reference 4 describes earlier studies with liquid-crystal nonlinear overlays and second response times.

An attraction of using semiconductor waveguides is the potential for integrating optical sources, detectors, and electrical components on the same substrate. Talk 11 discusses the problems and possibilities in great detail and concludes that semiconductor waveguide performance should eventually be comparable to that of $LiNbO_3$, the standard material for waveguide devices.

It is anticipated that the development of nonlinear optical guided-wave devices for serial processing will be very rapid, driven by the great success of optical fibers for long-distance communications and the anticipated demand for guided-wave optical interconnects within electronic computers.

c. Optics in Computers

The progression of optics within digital computers is likely to be guided-wave interconnects, free-space imaging interconnects, special-purpose optical processors, and finally, if ever, all-optical computers.

Guided-wave interconnects can use existing technology developed for optical communication links; namely, sources, modulators, optical fibers, and detectors. Intergration of all needed components is the objective of much of the current research and development.

Much less developed or accepted is the imaging of whole arrays of information from one chip or board to another. Spatial light modulators (talk 15) and detector arrays are essential for the light-electronics interfaces. If nonlinear arrays can be used to reduce the data, then a single detector or fewer-element detector arrays would suffice. Imaging interconnects would utilize the advantages of light beams: massively parallel, no interaction between beams passing through each other, and fastest propagation speed, for example. Dynamically programmable interconnects in which beams are redirected during computation can be conceived (talk 17), emphasizing that optics offers some unique possibilities.

Special-purpose optical add-ons to electronic computers are already being marketed (Ref. 5). Some operations that optics can do better (quicker, cheaper, smaller space) are farmed out to the optics device and the answer is fed back. The evolution of electronic computers is itself in this direction of parallel architecture and dedicated subprocessors, making the resistance to the use of an optical dedicated device much lower. The study of computer architecture especially designed to fully utilize the new possibilities with optics is very important (talk 18; Ref. 6).

Perhaps someday there may even be an all-optical computer. Talk 14 discusses this possibility with considerable optimism based on several facts: the electronic computer is in trouble not because of switching speed, but because of communication problems; optics is not starting from zero, since linear operations such as imaging and Fourier transformation have been performed for many years; photons cross with no interaction except for very localized regions where "exotic" nonlinear material is carefully placed; optics is naturally suited to massive parallelism so the optical logic components can be far inferior and still yield much better systems performance.

CONCLUSIONS

It is a near certainty that optical circuit elements and devices will find commercial and military applications in an increasing number of cases. Serial data processing for communications such as telephony, data transmissions, and connections between and within computers, will surely result in greater and greater demands for high-speed integrated source/modulator/fiber-interface/detector chips. Massively parallel systems utilizing imaging and nonlinear arrays will take longer to develop but will be necessary to handle pattern recognition or guidance decisions in real time. Whether or not there will ever be an all-optical computer seems rather irrelevant. The important point is that optical circuitry certainly has contributions to make. Let's see how well it can do.

RECOMMENDATIONS FOR FUTURE EFFORTS

Research and development should be directed toward the search for better nonlinear materials, the optimization of the growth of known materials, the optimization of nonlinear devices (design, coatings, etching, or background losses may degrade performance well below that predicted for the known nonlinearity in an ideal device), improvement of light-electronics interfaces, the construction and testing of prototype systems, and the development of new algorithms and architectures taking advantage of actual and perceived optical devices. The July 1984 IEEE Proceedings Special Issue on Optical Computing (Ref. 7) is an excellent place to find many more details (see also Refs. 8-11).

Concerted efforts such as the European Joint Optical Bistability effort or the Optical Circuitry Cooperative at the University of Arizona should accelerate progress in this field.

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APPENDIX A

DIGITAL OPTICAL CIRCUIT TECHNOLOGY PROGRAMME

Tuesday 11 September 1984

SESSION I – OPTICAL BISTABILITY
Chairman: Prof. Ir. D. BOSMAN (NE)

0900-0930 1. OPTICALLY BISTABLE DEVICES USING InSb
Prof. S. D. Smith, F. A. P. Tooley, A. C. Walker, A. K. Kar, J. G. H. Mathew, and B. S. Wherrett,
Physics Department, Heriot-Watt University, Riccarton, Edinburgh, UK

0930-1000 2. OPTICALLY NON-LINEAR AND BISTABLE BEHAVIOUR OF DIRECT GAP SEMICONDUCTORS
Prof. Dr. C. Klingshirn, K. Bohnert, and H. Kalt,
Physikalisches Institut der Universitaet, Frankfurt, and K. Kempf, LIFEF, Freiburg, FRG

1000-1030 BREAK

1030-1100 3. OPTICAL BISTABILITY IN $Cd_xHg_{1-x}TE$
Dr. A. Miller, D. Craig, G. Parry, J. G. H. Mathew, and A. K. Kar,
Royal Signals and Radar Establishment, Malvern, Worcs, UK

1100-1130 4. OPTICAL MODULATORS AND BISTABLE DEVICES USING MOLECULAR GASES
Dr. R. G. Harrison, W. J. Firth, and I. A. Al-Saidi, and E. Cummins,
Department of Physics, Heriot-Watt University, Riccarton, Edinburg, UK

1130-1200 5. AN EXPERIMENTAL NONLINEAR OPTICAL WAVEGUIDE DEVICE
Messrs. I. Bennion, M. J. Goodwin, D. J. Robbins, and W. J. Stewart, Plessey Research (Caswell) Ltd.
Allen Clark Research Center, Towcester, Northants, UK

1200-1400 LUNCH

1400-1430 6. STATIONARY PROPERTIES AND SWITCHING CHARACTERISTICS OF DISPERSIVE OPTICAL BISTABILITY IN CuCl
Dr. C. M. Bowden, J. W. Haus, US Army Missile Laboratory, Redstone Arsenal, C. C. Sung, Department of Physics, University of Alabama, Huntsville, AL, US

1430-1500 7. CAVITYLESS OPTICAL BISTABILITY IN SYSTEMS OF TWO-LEVEL ATOMS
Dr. C. M. Bowden, U.S. Army Missile Laboratory, Redstone Arsenal, AL, and F. A. Hopf, Optical Sciences Center, University of Arizona, Tucson, AZ. US. Presented by J. W. Haus.

1500-1530 BREAK

SESSION II – OPTICAL LOGIC
Session Chairman: Mr. B. L. DOVE (US)

1530-1600 8. PROSPECTS FOR PARALLEL NONLINEAR OPTICAL SIGNAL PROCESSING USING GaAs ETALONS AND ZnS INTERFERENCE FILTERS
Prof. H. M. Gibbs, J. L. Jewell, Y. H. Lee, G. Oldbright, S. Ovadia, N. Peyghambarian, M. C. Rushford, M. Warren, and D. A. Weinberger,
University of Arizona, Tucson, AZ, US and T. Venkatesan, Bell Communications Research, Murray Hill, NJ, US

1600-1630 9. ALL-OPTICAL LOGIC GATES WITH EXTERNAL SWITCHING BY LASER AND INCOHERENT RADIATION
Dr. S. D. Smith, F. A. P. Tooley, A. C. Walker, J. G. H. Mathew, M. Taghizadeh, and B. S. Wherrett,
Physics Department, Heriot-Watt University, Riccarton, Edinburg, UK

1640-1700 10. INTEGRATED ELECTRO-OPTICAL COMPONENTS USING DIELECTRIC SUBSTRATES
Dr. M. Papuchon, Y. Bourbin, S. Vatoux and C. Puech,
Optics Department, Thomson CSF, Orsay, FR

SESSION III – SOURCES, MODULATORS, AND DEMODULATORS
Chairman: Mr. I. W. Mackintosh (UK)

0830-0900 11. THE POTENTIAL OF SEMICONDUCTORS FOR OPTICAL INTEGRATED CIRCUITS
Messers. S. Ritchie and A. G. Steventon
British Telecom Research Lab, Ipwich, UK

0900-0930 12. MULTIPORT OPTICAL DETECTORS
Mr. N. G. Walker and J. E. Caroll
Engineering Department, Cambridge University, UK

0930-1000 13. PICOSECOND PHOTOCONDUCTIVE DEVICES FOR >10 GBIT/S OPTOELECTRONIC SWITCHING
Dr. G. Veith
Standard-Elektrik Lorenz AG, Stuttgart, FRG

1000-1030 **BREAK**

SESSION IV - ALL-OPTICAL SYSTEMS
Chairman: R. Klemm (FRG)

1030-1130 14. PROSPECTS OF THE DIGITAL OPTICAL COMPUTER
Prof. Dr. A. W. Lohmann, H. Bartelt, and J. Weigelt
Physikalishes Institut der Universitaet, Erlangen, FRG

1130-1200 15. DEFORMABLE MIRROR NEAREST NEIGHBOR OPTICAL COMPUTER
Dr. A. D. McAulay
Texas Instruments, Inc., Central Research Laboratories, Dallas, TX, US

1200-1230 16. OPTICAL TECHNIQUES FOR SIGNAL DISTRIBUTION AND CONTROL IN ADVANCED RADAR AND COMMUNICATION SYSTEMS
Prof. J. R. Forrest, Department of Electronic and Electrical Engineering, University College, London, UK

1230-1400 LUNCH

1400-1500 EEC PROJECT DISCUSSION
Prof. S. D. Smith,
Physics Department, Heriot-Watt University, Riccarton, Edinburgh, UK

1500-1530 BREAK

1530-1600 17. ELECTRO-OPTIC TECHNIQUES FOR VLSI INTERCONNECT
Dr. J. A. Neff,
Defense Advanced Research Projects Agency, DARPA/DSO, Arlington, VA, US

1600-1630 18. RESEARCH IN NUMERICAL OPTICAL COMPUTING AT THE OHIO STATE UNIVERSITY
Dr. S. A. Collins, Jr., S. F. Habiby, and A. F. Zwilling
Ohio State University, ElectroScience Laboratory, Columbus, OH, US

1630-1640 DISCUSSION OF CLOSELY COUPLED TWIN STRIPE LASERS WITH BISTABILITY
Prof. J. E. Carroll and I. H. White
University of Cambridge, UK

1640-1700 CLOSING CEREMONY

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Integrated optics	Optical modulators
Optical bistability	Optical sources
Optical computer	Optical waveguides
Optical demodulators	Parallel processing

14. Abstract

This Technical Evaluation Report, based on the 18 papers presented at the AGARD Avionics Panel Specialists' Meeting on Digital Optical Circuit Technology, makes evaluations and recommendations and draws conclusions. The Conference Proceedings for this Specialists' Meeting is published as AGARD CP-362.

The purpose of the Specialists' Meeting was to present the research and development status of digital optical circuit technology and to examine its relevance in the broad context of digital processing, communication, radar, avionics, and flight control systems implementation.

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